A POTENTIAL APPLICATION OF ACCELERATORS IN ATMOSPHERIC PHYSICS

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abstract

Artificial changes to the atmosphere's properties are difficult to achieve on anything other than a very small scale, however, air beam dumps from high-energy accelerators create enormous ionization levels, which could be used to influence thunderstorms or other atmospheric phenomena. The spatiotemporally confined air beam-dumps could virtually short-circuit the gigawatt global electrical circuit or simulate intense cosmic radiation ionization at low altitudes (which is normally removed by atmospheric screening). The ions formed will act as condensation nuclei in cloud formation. Induced air-radioactivity by electromagnetic showers is radiologically negligible and far below the maximum permissible concentrations. Some fifty accelerators exist in the $\sim$ GeV range (e.g. synchrotron radiation facilities), which could be utilized. Enhanced cosmic radiation observed during thunderstorms suggests that the atmosphere acts as a transient amplifier, which might be exploited by the use of accelerators. Intriguing atmospheric phenomena not replicable in the laboratory could also be investigated, power removed from the atmospheric circuit and methods of weather modification developed.

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1. Introduction

Atmospheric air ions are responsible for the electrical conductivity of air, and therefore the steady-state transfer of charge in the atmospheric electrical circuit [1, 2]. The formation of molecular ions (hereafter referred to simply as 'ions') in the atmosphere is caused naturally by a combination of cosmic rays, surface gamma radiation and diffusion of Radon isotopes in the boundary layer, but cosmic rays dominate ion production in the upper atmosphere. Note that the amplification factor, as a ratio of the energy of the latent heat released in the production of droplets to the energy to create the ion, can be as much as 10^{14}, assuming 1 to 100 ions trigger nucleation [3]. The suggestion here is to employ high-energy accelerators *directed upwards* from the surface, to cause an intense and rapid ion shower through much of the troposphere. Calculations suggest that this could be achieved with existing accelerator systems, and that it would be quite practical to cause substantial atmospheric changes with these systems, as well as with the larger accelerators planned for the future.

2. Atmospheric significance of ions

Studies of the possible long-term changes in air conductivity from radioactive decays of ^{85}Kr [4, 5], have suggested that at low levels of ionisation, effects on the atmospheric electrical system as a whole are negligible. Intense ion showers, however, might be expected to have a much greater effect. Additional ion production could lead to greater cloud production by heterogeneous nucleation, as addition of even a single ion can decrease the potential energy of an embryonic cluster of a few dozen molecules [3]. Excess atmospheric ionisation could also cause alternative discharge paths in thunderstorms, initiate electrical discharges, or lead to new atmospheric charge distributions by convective transport. Hence we now estimate at what atmospheric ion concentration the atmospheric effects would be significant.

The conductivity σ of air is given by the steady-state ion concentration, determined by ion production and loss (by recombination or aerosol attachment), by

$$\sigma = \frac{\mu e}{\alpha}[-\beta Z + \sqrt{(\beta Z)^2 + 4\alpha q)}] \quad (1)$$

where q is the volumetric ion production rate, α the ion-ion recombination coefficient, μ the ion mobility, β the ion-aerosol attachment coefficient, and Z the (monodisperse) aerosol number concentration. At large ionisation rates, the air conductivity will therefore scale as $\sqrt{q}$. The net ion production rate q_s expected from an atmospheric volume containing radioactive species of concentration of c decays (per unit time per unit volume) is $q_s = c \cdot E_R/w_i$, where w_i is the work done in air in forming an ion pair ($w_i \approx$ 35 eV), and E_R is the energy of the emitted radiation [6], i.e. the ionisation caused is linearly proportional to a radioisotope's air concentration. Hence the air conductivity will vary also as the square-root of the ion concentration produced by a shower. Figure 1 shows the vertical variation of air conductivity, in the presence of various levels of background ionisation q_b [7], which also illustrates the likely reduction in atmospheric columnar resistance with increases in q_b.

We shall now estimate what ion concentration would be required to short-circuit a thundercloud, extending the analysis of [8] to a cloud of finite dimensions [9]. Atmospheric ions are removed by three processes, ion-ion recombination, ion-aerosol attachment, or in-cloud ion-droplet attachment (scavenging). Their relative magnitudes are approximately similar, although in detail they depend on the aerosol and droplet size distribution, the amount of aerosol charging, and the electric field within the cloud. Assuming that there are equal concentrations per unit volume of positive and negative ions (n), the ion birth-death equation is

$$\frac{dn}{dt} = q_s - \alpha n^2 - \beta Z n - \gamma C n \tag{2}$$

with C water droplets per unit volume, and γ the ion-droplet scavenging coefficient. The ion mobility under standard conditions (20°C, 1013 mbar) is about μ_S=1.2x10^{-4}m^{2}V^{-1}s^{-1} [10], and the corresponding recombination coefficient is α_S=1.6x10^{-12}m^{3}s^{-1}. The ion-droplet attachment coefficient γ ≈2x10^{-13}m^{4}s^{-1}V^{-1}E, where E is the electric field strength [8].

In its mature stage, a thundercloud is considered to be of approximately 12 km in vertical extent [11], and to have a central temperature of about -18°C, in the region where charge exchange is occurring, with a corresponding pressure of about 350 mbar. Scaling the ion properties to this height gives μ(-18°C, 350 mbar)=3.36x10^{-4}m^{2}V^{-1}s^{-1} [12], α(-18°C)=2.0x10^{-12}m^{3}s^{-1} [13], and, for a 0.2 μm radius aerosol, β =1.9x10^{-11}m^{3}s^{-1} [14]. The electrical conductivity of air is $\sigma = 2en\mu$, (for for approximately equal ion concentrations n), where e is the charge of the proton, and up to the Ohmic saturation current, the conduction charge flux J_c in a field E is $J_c = \sigma E \approx 2ne\mu E$. The one-dimensional time evolution of the cloud's electric field [15] may be written as

$$\frac{dE}{dt} = \frac{-J_h f}{\epsilon_0} \tag{3}$$

where J_h is the hyrometeor charge flux causing the charge-exchange, and f is a factor to account for the non-infinite parallel plate nature of the cloud. (For a cloud of equal width and height, $f \approx 0.1$ [9]).

The field growth within the cloud is approximately exponential,

$$E \approx E_0 \exp(\xi t). \tag{4}$$

where ξ is chosen by consideration of the breakdown field in air (E_b=300 kV$\cdot$ m^{-1}), when the field growth ceases, and is ≈ 0.08 assuming a growth from 100 V$\cdot$m^{-1} in 100 s. J_h may be estimated from equations (3) and (4) as

$$\mid J_h \mid \approx \frac{\epsilon_0}{f}\frac{dE}{dt} = \frac{\epsilon_0}{f}\xi E. \tag{5}$$

If field growth within the storm is to occur, the necessary condition is $J_h \gg J_c$, *i.e.* that the cloud electrification current is considerably greater than the discharging current. Equating these two terms, the critical ion concentration n_c is

$$n_c = \frac{\epsilon_0 \xi}{2e\mu f}. \tag{6}$$

and the corresponding critical ionisation rate q_c at which $J_h = J_c$ is given from

$$q_c = n_c(\alpha n_c + \beta Z + \gamma C) \tag{7}$$

when the cloud *cannot* develop an electric field. Inserting values gives

$$q_c \approx 10^{13}\ m^{-3} s^{-1}$$

as the ionisation rate required by the shower to short-circuit the electrification process. We now consider if this can be achieved using a high energy accelerator system.

3. Ion production by high energy air showers

The air-showers starting from the Earth's surface will deposit their energy in the Troposphere (Fig. 2, 3), the region of cloud formation and thunderstorm activity. About 1 % of the initial electromagnetic energy, which is not negligible, remains to be deposited after $\sim 25\ X_0 = 925$ g/cm^2 (≈ 18 km) [16]. Most of the initial particle energy (E_R) is dissipated in the atmosphere by atomic/molecular ionization and excitation. We confine ourselves to electromagnetic showers here, since their environmental impact (i.e. from induced radioactivity) is negligible (section 4.); furthermore some fifty electron accelerators in the GeV range already exist or are under construction [17]. Part of the absorbed energy is released optically ($\lambda \approx 300 - 400$ nm and 0.5 % yield), and part is emitted as Cherenkov uv−light ($\lambda \leq 250$ nm and a relative yield of ~ 0.1 %) [18]. We assume therefore, that an incident 1 GeV $e^{\pm}$ will lead to the atmospheric release of :

a) $N^{ions} = E_R/w_i \approx 6 \cdot 10^7$ [electrons-ions],

b) $N^{Cherenkov} \approx 10^5$ [uv photons], and

c) $N^{fluorescence} \approx 2 \cdot 10^5$ [scintillation photons].

These numbers will scale linearly with the primary particle energy $E_R[GeV]$ and the flux of the incident particles. It is the intense *and* high energy accelerator beams with some $10^{11} - 10^{12}$ particles per bunch, which make the otherwise weak accelerator currents (with nanocoulomb charge and nanosecond duration bunches) of practical importance for atmospheric physics. The uv component could conceivably influence atmospheric chemistry.

For muons with energies above ~ 100 GeV, radiative processes become more important than ionization [19]. Those muons can escape from an accelerator or from external beam lines, which can then also initiate electromagnetic air showers (Fig. 3). We stress here that even though their radiological impact is likely to be negligible (section 4.), their potential atmospheric impact might not be, depending on the magnitude of conductivity changes due to ionization. So prospective muon colliders in the $\sim$ TeV range are of particular interest, since muons are highly penetrating. In addition, these high energy muons can escape from the earth's atmosphere, and the decay electrons will be highly suitable for simulating cosmic air showers. The range for ~ 100 GeV muons in the atmosphere and Earth's dipole magnetic field ($B_{max} \sim 10^{-4}$T) is effectively infinite in terrestrial terms. Therefore beams from existing high energy accelerators (and especially those from the future muon colliders [20]), could be used for air-showers not just locally, but effectively anywhere on the globe.

The total energy available, from a single bunch of particles of $\sim$ nanosecond duration in the GeV range, is $\approx 10^{20}$ eV. Such *spatiotemporally confined* energies are very rare in cosmic showers [21], scaling with $\sim 1/E_R^{2.7}$:

$$\sim 1/(100\ km)^2 - sr - year\ \ at\ \ 10^{20} eV\ \ and\ \ \sim 1/km^2 - sr - sec\ \ at\ \ 10^{15} eV\ .$$

Cosmic rays have previously been linked with atmospheric phenomena [22]. However, the net energy to be deposited with accelerator beam-dump within one ion lifetime in air (≈ 200 s [23]) can be enormously high ($\sim 10^{23} - 10^{27}$ eV). If we assume an air beam-dump energy equal to the energy stored in the beam of the planned 7 TeV LHC (CERN) machine (a $2 \cdot 10^{12}$ W pulse of ~ 90 μs), its isotropic light flash from atmospheric scintillation would be $\sim 10^{10}$ W. This compares with the optical power of natural lightning of $\approx 10^9 - 10^{11}\ W$ [24]. However, electron accelerators with $\sim GeV$ beam energy would seem to be quite adequate to produce atmospheric effects. To steer an electron beam of 1 and 10 GeV upwards, the radii of curvature inside a 5 T magnetic field are 0.6 m and 6 m respectively, while the energy loss due to synchrotron radiation is below 1% [19]. *Table 1* gives predicted charges released by air-ionization during a beam-dump for various accelerators, which are large compared with atmospheric charges. Assuming a maximum air shower *core* volume of $\sim 300 \times 300 \times 10000\ m^3$ (s. Fig. 3), the released ion-concentrations due to one single 12 ns LINAC pulse will be $\sim 10^9$ m^{-3} and for one LEP fill $\sim 10^{13}$ m^{-3}, within $\sim$ (20-100) μs (the shower propagation time). Within this relatively long time period, the transient ionisation rates of $\sim 10^{13} - 10^{17}$ m^{-3}s^{-1} are clearly above the critical value q_c of section (2). The associated *local and temporal* increase in air conductivity would be up to six orders of magnitude. Taking the smaller accelerator performances from *Table 1*, *i.e.* the LINACs with their ~ 100 Hz repetition rate [25], continuous ionisation could be maintained at a rate of $\sim (10^{11} - 10^{13})$ ion pairs m^{-3}s^{-1}, greater by $\sim 10^3 - 10^5$ than that caused by cosmic rays and Radon (the major natural sources of air ionisation) [26]. However, with the intense Synchrotron Radiation Facilities, e.g. ESRF [25], the predicted continuous ion production rate can be as large as 10^{15} m^{-3}s^{-1} (s. *Table 1*).

Transient electric field strengths of $\sim 10 - 100$ kV/cm, likely to exist during lightning discharges [2, 27], exceed the breakdown limit of air (some kV/cm), and thus could lead to an avalanche of secondary electrons and ions, i.e. a *plasma*. This would be further enhanced by the externally injected charges, and an amplification factor of $10^4 - 10^6$ has been found in proportional chambers. In addition, the relativistic electrons and positrons from the shower are accelerated inside such fields, which agrees at least qualitatively with the observed bursts of photons (up to $\sim 100\ keV$) [28] correlated with lightning flashes; most of the photons would be absorbed close to where they were formed, causing still more ionisation charges.

4. Induced air-radioactivity

Radioactivity produced by high energy electromagnetic showers (e) is orders of magnitude lower than that from energetic protons (p). The (short lived) air radioactivity expected from a beam dump of $\sim 10^{23}\ eV$ (*e.g.* LEP's stored beam energy) is ~ 1 kBq/m^3 (or about ~ 1 Ci in total), which corresponds to $\sim 0.25\ \mu$Sv/h = 25 μrad/h [25]. For comparison, the dose due to natural cosmic rays at 2 km and 5 km altitude, is ~ 5

μrad/h and ~ 20 μrad/h, respectively [29]. Assuming 1000 such beam-dumps per day, it is important to observe that the radioactive concentration is still ~ 10 to 100 times below the maximum permissible concentration (MPC) at accelerator sites for whole-body exposure for a 40hour week [30].

The chief isotopes produced would be the pure β^+ emitters ^{13}N (85%) and ^{15}O (14 %), with half-lives of 10 min and 2 min, respectively. Thus, no permanent effect would result, and the radioactive isotopes would appear well above $\sim 3\ X_0$ or ~ 1 km altitude below which self-absorption by the atmosphere would further reduce their radiological impact at the Earth's surface. The radiological impact of energetic muons would also be negligible, since the physics of the muon interaction with matter is very similar to that of electrons [16]. For comparison, the existing long lived (~ 11 years) atmospheric radioactive ^{85}Kr is $\sim 10^8$ Ci [4]. During an air-beam-dump however, it would be prudent to restrict access to the region used, because of the intense radiation.

5. Conclusion

Our calculations suggest that the accelerator performance required in order to perturb atmospheric phenomena would be quite modest. Construction of compact, (even portable), electron accelerators in the ~ 0.1 to 1 GeV range would then become of practical importance [31]. These estimates demonstrate that the charging processes of thunderstorms could be directly altered by the use of a high energy accelerator, directed upward, and the Monte-Carlo simulations show that the shower would penetrate far enough into the cloud. To minimize the risk of unforeseen adverse environmental affects it would be essential to start such investigations with low beam intensity and energy. There is also the possibility that at some energies lightning would be initiated by the shower, rather than the usual use of rocket-bourne wires of ~ 200 m [32]. Initiating discharges by this means to a fixed, high melting -point metal plate, could provide a method of extracting energy from the atmospheric electrical system. Correlations could also be examined using *cosmic air shower detector arrays* [21], to measure the energy, timing and direction of the cosmic event together with any meteorological phenomena triggered or changed by the ion shower. The use of accelerators in this way could lead to investigation of other intriguing atmospheric phenomena not replicable in the laboratory [33].

Table 1.

Ionization charges ($Q = 2\times$absorbed energy$/w_i$) expected to be created in air for a number of accelerators at CERN and at SLAC [25], covering a wide energy range. (The 2 μs, 23 μs and 90 μs used in the 3rd column is the time needed to empty all stored bunches inside the ring accelerator, while the following $\sim$ ns/ps time intervals refer to one single bunch, i.e. the time resolving power). The free charges created increase for oblique muon injection angles at $\sim$ TeV accordingly.

Accelerator	Energy	$Q/\Delta t$ [1)]		
CERN/LINAC (e)	600 MeV	1 C/s	or	10 mC/12 ns
SLAC/LINAC (e)	7 GeV	300 C/s	or	3 C/3 ps
CERN/PS (e)	3.5 GeV	1.3 C/2 μs	or	0.16 C/0.5 ns
CERN/SPS (e)	20 GeV	6 C/23 μs	or	0.7 C/130 ps
ESRF (e)	6 GeV	10^5 C/s	or	10 C/3μs
CERN/LEP (e)	55 GeV	10^3 C/90 μs	or	250 C/50 ps
CERN/LHC (p)	7 TeV	10^7 C/90 μs	or	3400 C/250 ps
Muon Collider	$\sim$ 2 TeV	$\sim 10^4$ C/s		

[1)] For comparison, note :

a) the mean charge in a lightning flash is [23] $\sim$ 16 C,

b) the separated charges of a typical thundercloud are [2] $\sim$ 100 C,

c) the total Earth's surface charge is [4, 23] $-5 \cdot 10^5$ C, and

d) the total charge in the atmosphere is [4] $\sim 7 \cdot 10^5$ C.

Figure captions

Figure 1. Atmospheric air conductivity plotted as a function of vertical height, in the presence of constant background ionisation rates q_b of 0, 10^{10} and 10^{14} $\mathrm{m}^{-3} \cdot s^{-1}$. The corresponding integrated columnar resistances are $1.2 \cdot 10^{17}$, $2.4 \cdot 10^{15}$ and $2.4 \cdot 10^{13}$ Ω respectively.

Figure 2. Part of the atmospheric electrical global circuit. Large arrows indicate flow of positive charge. The comibined global thunderstorms represent the $10^8 - 10^9$ V electrical generator [1, 2]. Shower profiles from a high energy cosmic event (right) and an accelerator beam dump (left) are inserted (not to scale).

Figure 3. Monte Carlo simulation (GEANT3 [34]) of the development of high energy electromagnetic air-showers. The electrons/muons enter the atmosphere vertically at a height of 500 m. The cutoff energy of the shower particles ($\gamma, e^{\pm}$) is at 1 MeV. Simulated number of showers: a) - b) 1000, c) 100, d) 10 and e) - h) 100. The longitudinal maximum of the electron air shower in radiation lengths is at $X^{max}[X_0] \approx 1.5 \cdot ln(E/E_c)$. The radiation length of air at STP is $X_0 = 37\ g/cm^2$ or 304 m, and $E_c = 81\ MeV$. The main transverse development scale of the shower is given by the *Moliere radius* R_M, which for air is $R_M \approx 80\ m$ [19], hence the maximum ionization inside the core of the electron shower could be up to ~ 10 times greater than that considered in the text.

References

[1] R. Markson, Nature **273** (1978) 103, R. Markson and M. Muir, Science **208** (1980) 979, and references therein.

[2] M. J. Rycroft, J. Atm. Terrest. Phys. **56** (3) (1994) 343.

[3] B. A. Tinsley and G. W Deen, J. Geophys. Res. **96** (D12) (1991) 22283.

[4] R. G. Harrison and H. M. ApSimon, Atmospheric Environment **28** (4) (1994) 637.

[5] W. L. Boeck, Science **193** (1976) 195.

[6] L. G. Christophoru, *Atomic and Molecular Radiation Physics*, Wiley, New York (1970).

[7] R. G. Harrison, Comment on Geophys. Res. Lett. **20** (13) (1993) 1363 (in press, 1994).

[8] J. D. Spangler and C. E. Rosenkilde J. Geophys. Res **84** (1979) 3184.

[9] A. J. Illingworth and J. Latham, J. Atmos. Sci. **32** (1975) 2206.

[10] V. A. Mohnen, *In* Proc. 5th Int. Conf on Atmospheric Electricity, Garmisch-Partenkirchen (1974) 1.

[11] R. R. Rogers and M. K. Yau, *A short course in cloud physics*, Pergamon, Oxford (1989).

[12] C. F. Clement and R. G. Harrison, *Radioactivity and Atmospheric Electricity*, Harwell Laboratory Report AERE M3770 (1990).

[13] R. C. Callahan, S. C. Coroniti, A. J. Parziale and R. Patten, J. Geophys. Res. **56** (1961) 545.

[14] R. Gunn, J. Coll. Sci **10** (1955) 107.

[15] J. Latham and B. J. Mason, Proc. R. Soc. Lond. **A266** (1961) 387.

[16] C. W. Fabjan and R. Wigmans, Rep. Progr. Phys. **52** (1989) 1519, and C. W. Fabjan, CERN 94-04 (1994) 77.

[17] R. P. Walker, CERN 94-01 (1994) 437.

[18] R. M. Baltrusaitis et al., N. I. M. **A240** (1985) 410, and
M. Bott-Bodenhausen et al., N. I . M. **A315** (1992) 236.

[19] K. Hikasa et al., Phys. Rev. **D45**, (1992) III. 1-44.

[20] D. V. Neuffer, CERN - 94 - 03 (1994) 49, W. A. Barletta and A. M. Sessler CERN - 94 - 03 (1994) 145, and S. Chattopadhyay et al., CERN - 94 - 03 (1994) 439.

[21] D. J. Bird et al., Phys. Rev. Lett. **71** (1993) 3401, T. K. Gaisser et al., Phys. Rev. **D47** (1993) 1919, G. L. Casidday et al., Astroph. J. **356** (1990) 669 and W. I. Axford, Astrophys. J. Suppl. **90** (1994) 937.

[22] B. A. Tinsley, G. M. Brown, P. H. Scherrer, J. Geophys. Res. **94** (D12) (1989) 14783, B. A. Tinsley, EOS Trans., Amer. Geophys. Union **75** (32) (1994) 369.

[23] C. W. Allen, Astrophysical Quantities, 2nd Edition, The Athlone Press, London (1963).

[24] Y. Q. Li et al., J. Geophys. Res. **96** (1991) 1315.

[25] The LEP Injector Study Group, CERN - LEP / TH / 83 - 29 (1983), J. T. Seeman et al,, SLAC - PUB - 6312 / LBL - 33456 (1993), R. Haensel, N.I.M. **A 266** (1988) 68 and Europhys. News **25** (1994) 133.

[26] E. A. Martell, J. Geophys. Res. **90** (D4) (1985) 5909, and M. Makino and T. Ogawa, *ibid* **90** (D4) (1985) 5961.

[27] N. D' Angelo, Ann. Geophys. **5B** (1987) 119.

[28] M. P. McCarthy and G. K. Parks, J. Geophys. Res. **97** (D5) (1992) 5857 and Geophys. Res. Lett. **12** (6) (1985) 393, G. E. Shaw, J. Geophys. Res. **72** (1967) 4623.

[29] M. Eisenbud, Environmental Radioactivity, McGraw-Hill, New York (1963) 167.

[30] W. P. Swannon, IAEE-Technical Report No. 188, Vienna (1979) 128-142.

[31] K. Zioutas, Phys. Lett. **A189** (1994) 460.

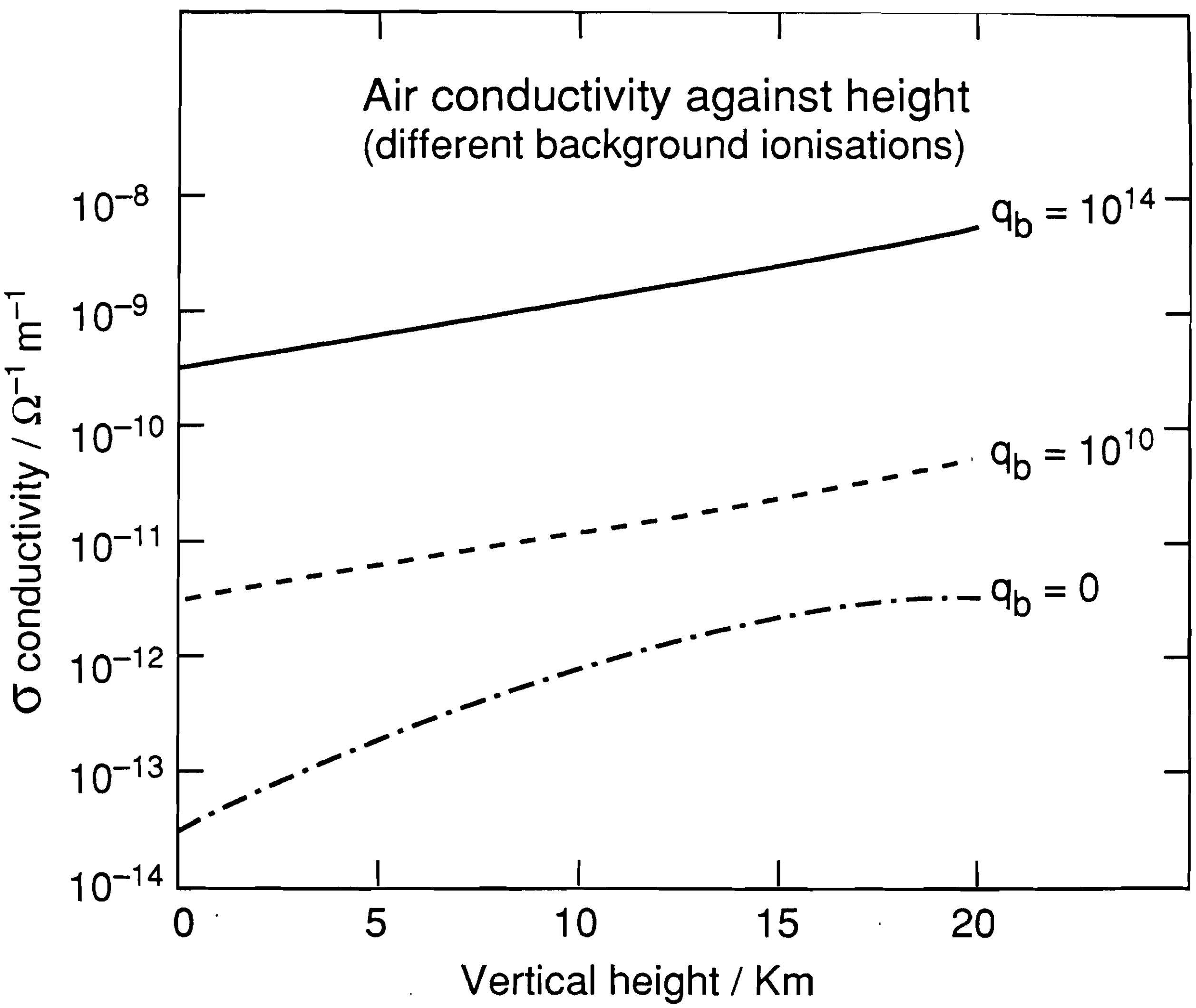
[32] P. Hubert et al., J. Geophys. Res. **89** (D2) (1984) 2511, and
V. Mazur, L. H. Ruhnke, *ibid* **98** (D7) (1993) 12913.

[33] For example : J. R. Winckler et al., J. Geophys. Res. **98** (D5) (1993) 8775, K. V. Beard and H. T. Ochs III, J. Appl. Meteor. **32** (1993) 608, C. P. R. Saunders *ibid* **32** (1993) 642, T. C. Foster and J. Hallet, *ibid* **32** (1993) 716, J. Eichmeyer and H. Baumer, Naturwissenschaften **77** (1990) 164, and B. M. Smirnov, Phys. Rep. **224** (4) (1993) 151.

[34] R. Brun et al. CERN - DD / EE / 84 - 1 (1984).

Acknowledgment

We thank Dr. Andreas Gougas for his rapid Monte Carlo simulations. K. Z. thanks the Greek Agency for Research and Technology for financial support.



Air conductivity against height
(different background ionisations)
$q_b = 10^{14}$
$q_b = 10^{10}$
$q_b = 0$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
σ conductivity / Ω^{-1} m^{-1}
0
5
10
15
20
Vertical height / Km

Figure 1.

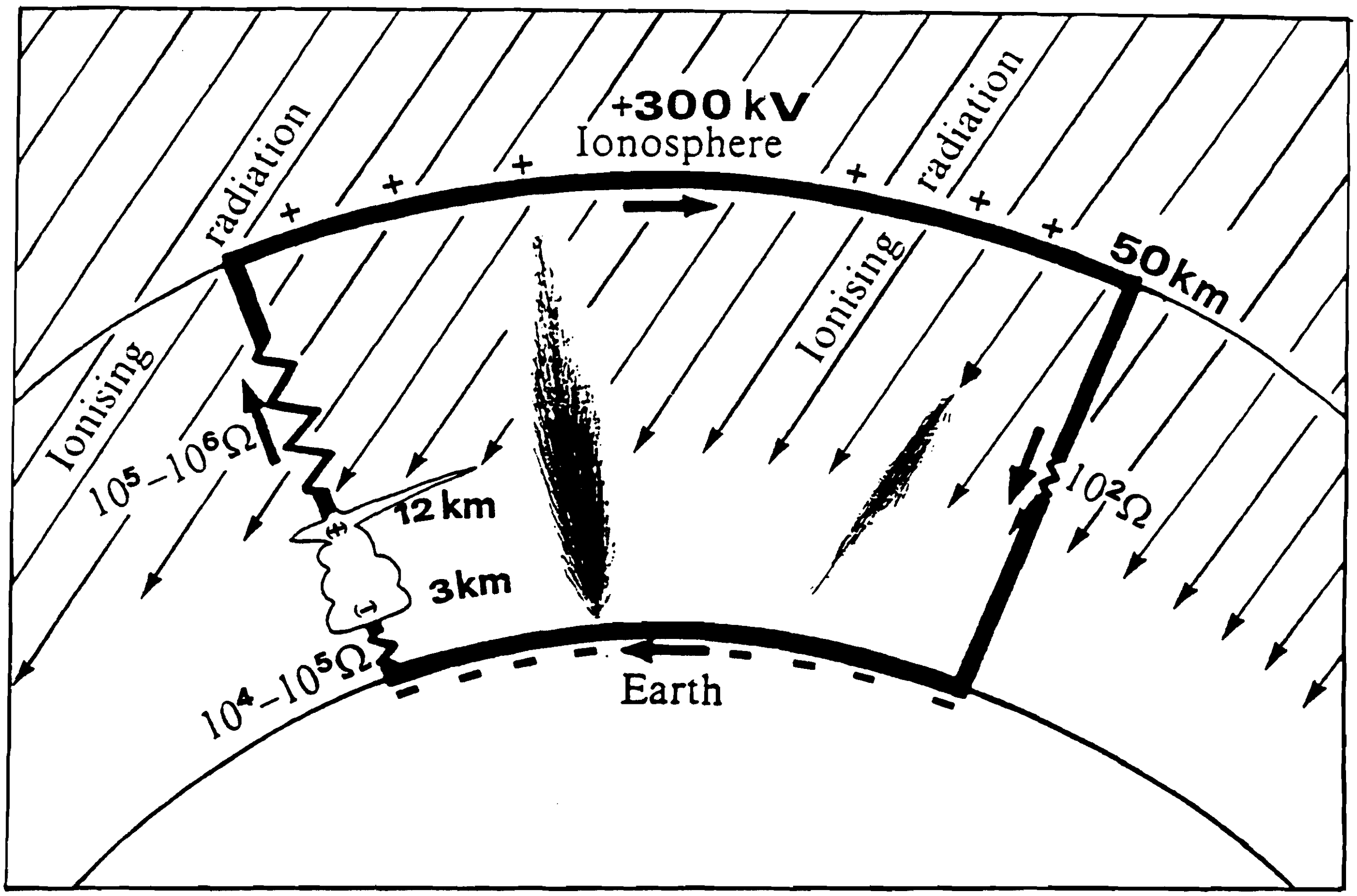

+300 kV
Ionosphere
Ionising radiation
Ionising radiation
50km
$10^5-10^6\Omega$
12 km
3km
$10^2\Omega$
$10^4-10^5\Omega$
Earth

Figure 2.

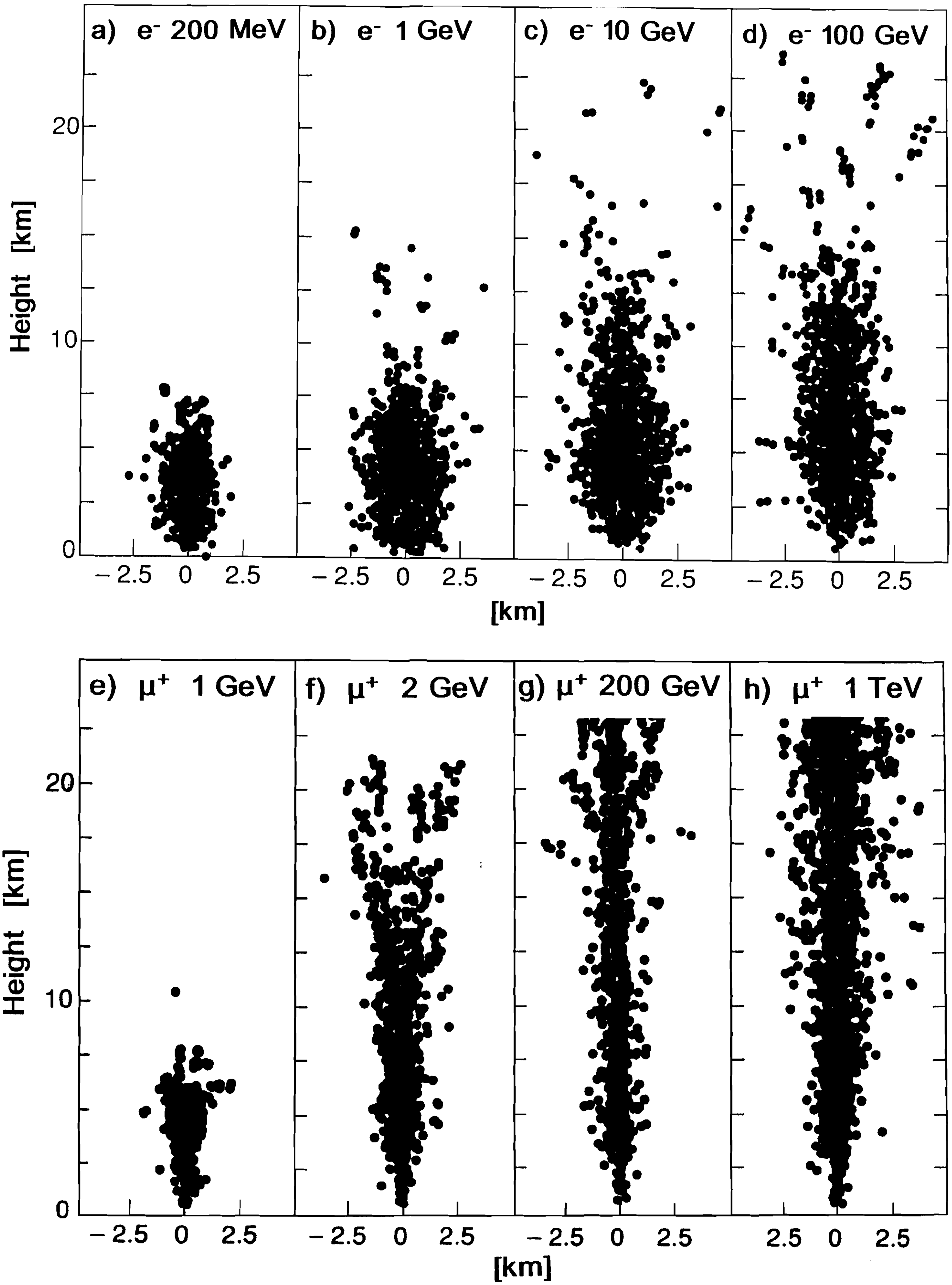

a) e⁻ 200 MeV
b) e⁻ 1 GeV
c) e⁻ 10 GeV
d) e⁻ 100 GeV
e) μ⁺ 1 GeV
f) μ⁺ 2 GeV
g) μ⁺ 200 GeV
h) μ⁺ 1 TeV
Height [km]
[km]
0
10
20
−2.5
0
2.5

Figure 3.